Appendix B. Recommended Lab Test Outline – AM-band

REVISION #2 October 8, 1998	IBOC LABORATORY TEST GUIDELINES-AM BAND				
Test Group	Test & Impairment	TEST PROCEDURE Note: The audio impairment test material will be used for the TOA test (see test K).	Type of Evaluation	Signal Level	Test Results Data to be Recorded
A Calibration	1 Power (each test day or as needed)	1. IBOC analog and digital power will be read separately. 2. The digital average and peak power will be measured for each system at least once.	Objective	NA	Power level
	2 Spectrum (each test day or as needed)	1. A spectrum analyzer plot of the system RF spectrum will be taken for each test. 2. The spectrum analyzer will be set up in accordance with FCC 73.44.	Objective	M	Laboratory log
	3 TOA (daily or as needed)	Gaussian noise will be added to the signal in 0.25 dB steps until TOA occurs (See test B). Test C-4, weak signal test, will also be conducted.	EO&C and Objective	M	TOA level
	4 Audio recording (as needed)	An audio recording will be made of all of the proponent audio channels (analog and digital).	EO&C	M & W	Digital audio recording for the test record
	5 Proof IBOC (weekly)	During the analog compatibility tests, a proof of performance test will be conducted weekly on the analog portion of the proponent IBOC systems. A high quality demodulator will be used for this test.	Objective	Varying	Record of frequency response, separation, and distortion for the test record
	6 Reference analog TX total proof	If a reference transmitter is used, a proof of performance test will be conducted on this transmitter, with and without subcarriers, prior to the compatibility tests. Both subcarrier groups will be calibrated.	Objective	NA	Test records
	7 Monitor calibration (weekly or as needed)	The analog modulation monitors will be calibrated monthly.	Objective	NA	Calibration results recorded in laboratory test record
	8 Test bed calibration (monthly)	All of the critical components in the test bed, transmission path simulators, attenuators, combiners, filters, generators, and measuring instruments, will be calibrated on a monthly schedule.	Objective	NA	Calibration record in test record

REVISION #2 October 8, 1998		IBOC LABORATORY TEST GUIDELINES-AM BAND			
Test Group	Test & Impairment	TEST PROCEDURE Note: 1. Glockenspiel will be used for the digital audio impairment tests. 2. The detailed procedure for noise measurements will be supplied. See Appendix S of the Digital Audio Radio Laboratory Tests Report, August 11, 1995. 3. Clipped pink noise will be used for the host analog signal.	Type of Evaluation	Signal Level dBm	Test Results Data to be Recorded
B Impairment tests for character-ization of DAR signal failure	1 Noise	1. Gaussian noise will be increased to TOA & POF (0.25 dB steps) and the levels logged. 2. From the TOA the noise will be increased in 0.5 dB steps until the noise is 0.5 dB beyond POF. For each 0.5 dB step a digitally recording will be made for expert subjective assessment.	EO&C	M	Noise level at TOA & POF

REVISION #2 October 8, 1998	IBOC LABORATORY TEST GUIDELINES-AM BAND				
	Test & Impairment	TEST PROCEDURE Notes: 4. Glockenspiel will be used for the digital audio impairment tests. 5. The host analog modulation will be clipped pink noise.	Type of Evaluation	Signal Level	Test Results Data to be Recorded
C DAR with special impairment	1 Impulse noise	4. A generator capable of generating 100 nanosecond wide pulses with a rise and decay time of 3 to 4 nanoseconds will be used for the test. Pulse rates between 100 Hz to 1000 Hz will be used. All systems will be tested with a 120 Hz signal. 5. The pulse generator output will be mixed with the DAR signal. 6. The amplitude of the pulses will be increased until the laboratory specialist hears the TOA.	EO&C	M	Pulse amplitude in Volts P-P at TOA
	2 Weak signal	4. Starting with a medium signal level, the signal will be reduced to TOA & POF (0.25 dB steps). 5. A single audio impairment recording will be used for this test. 6. Characterize failure between TOA and POF in 0.5 dB steps. Note- weak signal test should be used to monitor the performance of the receiver hardware but should not be used to evaluate the proposed system.	EO&C	Varying	Signal level at TOA & POF

REVISION #2 October 8, 1998		IBOC LABORATORY TEST GUIDELINES-AM BAND			
Test Group	Test Number and Impairment	TEST PROCEDURE Note: 1. Two additional IBOC transmitters supplied by each proponent will generate the undesired DAR signals. 2. The desired host analog signal will be modulated with clipped pink noise. 3. Glockenspiel will be used for the digital audio impairment tests.	Type of Evaluation	Sig. Level	Test Results & Data to be Recorded
D DAR -> DAR	1 Co-channel	1. The undesired co-channel DAR signal will be increased until the TOA and POF are heard by the lab specialist (0.25 dB resolution). 2. Co-channel signal failure will be characterized in 0.5 dB steps from TOA to POF using the five-step CCIR impairment scale.	EO&C in Lab	M	D/U & levels at TOA & POF Co-channel failure characteristics
	2 First adjacent	1. The undesired lower first adjacent composite IBOC signal will be increased in 0.5 dB steps until the TOE and POF are found. 2. The test will be repeated with an upper first adjacent undesired signal. 3. The test will be repeated with simultaneous upper and lower first adjacent undesired signals.	EO&C in Lab	M	D/U & levels at TOA & POF
	3. Second adjacent	1. The undesired lower second adjacent composite IBOC signal will be increased in 0.5 dB steps until the TOE and POF are found. 2. The test will be repeated with an upper second adjacent undesired signal. 3. The test will be repeated with simultaneous upper and lower second adjacent undesired signals.	EO&C in Lab	M	D/U & levels at TOA & POF
	4 Third adjacent	1. The first part of this test will be conducted with a minimum out-of-channel power. 2. The undesired lower second adjacent DAR signal will be increased in 0.5 dB steps until the TOA and POF are observed. 3. The test will be repeated with an upper third adjacent undesired signal. 4. Simultaneous upper and lower second adjacent tests will be conducted. 5. The tests will be repeated with the undesired signal's out-of-channel power increased in 5 dB steps until TOA and POF are detected in the desired IBOC audio.	EO&C in Lab	M	D/U & levels at TOA & POF Third adjacent D/U with and without out-of-band components

REVISION #2 October 8, 1998		IBOC LABORATORY TEST GUIDELINES - AM BAND			
Test Group	Test & Impairment	TEST PROCEDURE Notes: 1. These tests will compare the IBOC to analog with the analog to analog interference	Type of Evaluation	Desired Signal Level	Test Results Data to be Recorded
F DAR -> Analog (interference to an analog receiver with no other impairments)	1 Co-channel objective	1. The three AM receivers characterized in test L will be used for the AM band tests. 2. The desired AM transmitters will be set for 100% modulation. The desired transmitter will not be modulated. 3. The CCIR recommendation 412-4 weighting filter will be used for the program channel S/N measurements. 4. Increasing the undesired signal until the resulting audio signal/noise ratios are 25 and 40 dB (QPK), the D/U will be measured for the interference combinations: analog -> analog, and the DAR -> analog.	Objective	M	D/U at specified S/N for A -> A and D -> A .
	2 1st & 2nd adjacent	1. The first and second adjacent channel procedures are the same as the co-channel procedures in F.1.1. The first and second adjacent channel measurement will be made with a single undesired signal operating above and below the desired signal frequency.	Objective	M	D/U at specified S/N for A -> A and D -> A
	3 Co-channel	1. The receivers used in step F.1.1 will be used for the subjective tests. 2. Classical music, rock music, and silence will be used for the desired channel analog audio. 3. The test will be conducted using the D/U that produced 25 dB and 40 dB audio S/N in test F-1. 4. The A to A reference and the test will be recorded on digital tape for demonstration or evaluation.	Subjective EO&C	M	Recordings for industry evaluation
	5 1st & 2nd adjacent	1. The subjective adjacent channel tests will use the procedures outlined in F.1, F.2, and F.3.	Subjective EO&C	M	Recordings for industry evaluation

REVISION #2 October 8, 1998 IBOC LABORATORY TESTS GUIDELINES - AM BAND

Test Group	Test & Impairment	TEST PROCEDURE	Type of Evaluation	Desired Signal Level	Test Results Data to be Recorded
		Note: 1. The undesired analog signal will be modulated with processed rock stereo. 2. The host analog will be modulated with clipped pink noise. 3. Glockenspiel will be used for the digital audio impairment test.			
H Analog -> DAR (no other impairments)	1 Co-channel	1. The undesired co-channel analog standard AM signal will be increased in 0.5 dB steps until the TOA and POF are found.	EO&C in lab	M	D/U at TOA & POF
	2 1st adjacent	1. The undesired lower 1st adjacent analog standard AM signal will be increased in 0.5 dB steps until the TOA and POF are found. 2. This test will be repeated with an upper 1st adjacent undesired signal.	EO&C in lab	M	D/U at TOA & POF.
	3 Simultaneous upper and lower 1st adjacent	1 Simultaneous upper and lower 1st adjacent analog signals will be increased until the TOA and POF are heard (0.5 dB steps).	EO&C in lab	M	D/U at TOA & POF.
	4 2nd adjacent	Note - this test will be conducted on both upper and lower 2nd adjacent channels. 1. The undesired analog signal will be increased until the TOA and POF are observed (1.0 dB steps). 2. Simultaneous upper and lower second adjacent tests will be conducted.	EO&C in lab	M	D/U at TOA & POF

REVISION #2 October 8, 1998	IBOC LABORATORY TEST GUIDELINES - AM BAND				
Test Group	Test & Impairment	TEST PROCEDURE Note: 1. The impairment audio will be Mozart track 67 on the SQAM disk. 2. The host analog channel will be modulated with clipped pink noise. 3. If clipped pink noise is heard during the test, the test will be repeated with the impairment audio simultaneously transmitted on the digital and host analog channels. 4. Each test will be repeated at least five times and the results averaged.	Type of Evaluation	Desired Signal Level	Test Results Data to be Recorded
J DAR acquisition and reacquisition tests	1 Simulated weak signal failure and acquisition	1. Noise will be added to the signal in 0.25 dB steps until POF is found. The POF level will be recorded. 2. The DAR transmitter will be disconnected from the receiver for one (1) second to assure loss of lock. 3. The test will be repeated with the transmitter disconnected from the receiver for thirty (30) seconds to assure loss of lock. 4. Three tests will be conducted with the noise reduced in 2dB, 4dB, & 6 dB steps below POF for each test. 5. The signal will be reconnected to the DAR receiver, and acquisition time will be recorded for each noise level. Acquisition is audio with some impairments. The reproduced audio will be graded using the CCIR five-point impairment scale.	EO&C in lab	M	Acquisition time at each noise level and disconnect time.

REVISION #2 October 8, 1998	IBOC LABORATORY TEST GUIDELINES-AM BAND				
Test Group	Test Number and Impairment	Test Description	Type of Evaluation	Sig. Level	Test Results & Data to be Recorded
K DAR quality	1. Audio test segments Quality Impairment	1. The nine quality segments selected by the DAR Subcommittee will be used for the quality tests. 2. Glockenspiel will be used for the impairment tests.	NA	NA	NA
	2 Quality transmission test	1. The quality test materials selected in test K-1 will be transmitted through each DAR system and recorded digitally. 2. Each recorded segment will then be sent to a subjective assessment laboratory.	Subjective EO&C in Lab	M	Assessed using the ITU-R continuous 5-grade impairment scale (See Appendix U of the DAR Subcommittee Laboratory Tests Report)

Quality Audio Test Segments Selected by the DAR Subcommittee		
Description	Duration	Source
Dire Straits cut	30s	Warner Bros. CD 7599-25264-2 (track 6)
Pearl Jam cut	30s	Sony/Epic CD ZK53136 (track 3) with processing[1]
Sounds of water	30s	Roland Dimensional Space Processor Demo. CD
Glockenspiel	16s	EBU SQAM CD (track 35/Index 1)
Bass Clarinet arpeggio	30s	EBU SQAM CD (track 17/Index 1) with processing1
Music and rain	11s	AT&T mix
Susan Vega with glass	11s	AA&T mix
Muted trumpet	9s	Original DAT recording, University of Miami
Harpsichord arpeggio	12s	EBU SQAM CD (track 40/Index 1)

[1]Processing chain used: Aphex Compellor Model 300 (set for leveling only)
Dolby Spectral Processor Model 740
Aphex Dominator II Model 720

REVISION #2		IBOC LABORATORY TEST GUIDELINES - AM BAND	October 8, 1998		
Test Group	Test & Impairment	TEST PROCEDURE Notes: 1. The AM receiver compatibility performance tests are those outlined in the August 11, 1995 EIA DAR laboratory test report. 2. Analog program channel compatibility receiver noise tests will use quasi-peak detection and a CCIR weighting filter.	Type of Evaluation	Desired Signal Level	Test Results Data to be Recorded
L DAR -> Analog (IBOC -> host analog)	1 IBOC to host analog	1. Three representative AM receivers will be used for the compatibility tests. 2. The host AM transmitters will be set for 100% modulation with 1 kHz tone. The host analog transmitter will not be modulated. 3. For each of the compatibility receivers the audio S/N will be measured with and without the digital IBOC signal. The host AM to digital power ratio used in the performance test will be used for the compatibility tests. If the proponent elects to use multiple analog to digital ratios for the compatibility tests, the performance tests will also be conducted at these ratios.	Objective	S	AM audio S/N with and without
	2 IBOC to host analog	1. The same receivers used for test L.1 will be used for this test. 2. The desired audio signal will be moderately processed. 3. Classical music, rock music, silence, and spoken voice will be used for the audio. 4. The host and reference AM transmitters will be set for a 100% modulation with a 1 kHz tone. 5. For each analog receiver test, a digital audio recording will be made of the host IBOC analog audio signal with the digital signal turned on and off.	Subjective EO&C	S	Recordings for further subjective assessment or demonstration

REVISION #2		IBOC LABORATORY TEST GUIDELINES-AM BAND			October 8, 1998
Test Group	Test	TEST PROCEDURE Note: 1. The analog signal will be heavily modulated with processed rock music. 2. The DAR signal will be modulated with the primary impairment audio test material.	Type of Evaluation	Desired Signal Level	Test Results & Data to be Recorded
M Analog -> DAR Analog to host IBOC	1 Host analog to IBOC digital with no other impairments	1. The host IBOC analog modulation will be set for 100% with heavy processing, and the lab staff will listen for digital impairments. 2. If impairments are heard the analog modulation will be reduced until no impairments are heard. 3. If impairments are not heard in step #1, the AM modulation will be increased until impairments are heard or 150 % modulation is reached. 4. The test results will be recorded on digital audio tape (DAT).	EO&C in lab	M	Modulation percentage verses impairments

Appendix C. Analog Receiver Selection (Compatibility Testing)

The suggested test procedures described in Appendices A (FM) and B (AM) include compatibility tests designed to determine the effect that IBOC DAB has on existing analog main channel audio signals. The NRSC recommends that these tests be done using commercially-available analog receivers representative of a cross-section of receivers in use by consumers since, during the initial and transitional phases of IBOC DAB service introduction, these are the receivers which will primarily be in use, and therefore of primary interest with respect to analog compatibility.

In previous NRSC IBOC DAB tests, five FM and three AM radios were selected for use in compatibility testing, listed in Table C-1.[2] For FM, radios were selected from four categories: auto, portable, home Hi-Fi (high end), and home Hi-Fi (competitive). Two automobile radios were selected because of their large consumer populations and because of their dramatically different stereo-to-mono "blend" implementations. These auto radios also showed high adjacent channel rejection. The portable and personal portable use similar circuitry and have less adjacent channel rejection. The high end home Hi-Fi radios had good 2nd adjacent channel rejection, but exhibited first adjacent channel rejection characteristics similar to that found in the portable and home radios.

Table C-1. Analog Receivers Used in NRSC IBOC DAB Tests (1995)

CATEGORY	MAKE & MODEL	FM	AM
Auto	Delco model # 16192463	✔	✔
Auto	Ford model #F4XF-19B132-CB	✔	
Portable	Panasonic RX-FS430	✔	✔
Home Hi-Fi (high end)	Denon TU-380RD	✔	✔
Home Hi-Fi (competitive)	Pioneer SX-201	✔	

Table C-2 shows the result of the FM -> FM D/U tests that were conducted using the five radios. For the D/U measurements, the undesired signal RF level was adjusted for a 45 dB signal-to-noise ratio in the main channel audio of the desired signal. The audio noise measurements were made using quasi-peak detection, a 15 kHz low pass filter, and the CCIR filter. The desired signal level was -62 dBm. Antenna matching networks were used when needed. The portable and home receivers were tested in a shielded box that eliminated interference from other electronic devices in the laboratory. The two auto radios did not need additional shielding.

[2] See "Consumer Electronics Group, Electronic Industries Association, Digital Audio Radio Laboratory Tests - Transmission Quality Failure Characterization and Analog Compatibility, August 11, 1995" for additional information. Appendix H contains characterization data on the receivers in Table C-1.

Table C-2. FM Analog-to-analog D/U test results

- D/U values at which main channel audio signal achieves a 45 dB S/N ratio
- Test data from 1995 IBOC DAB laboratory tests (see footnote 2)

RECEIVER	CO-CHANNEL (D/U, DB)	1ST ADJ. CHANNEL (D/U, DB)	2ND ADJ. CHANNEL (D/U, DB)	113 KHZ TEST (S/N, DB)
Delco	36.2	4.7	-45	No change
Ford	35.2	-6.1	-45.3	No change
Panasonic	40.9	27.3	-10.1	33.6
Denon	43.4	18.0	-28.9	34.0
Pioneer	44.2	26.6	-15.0	33.1

Additional information regarding receivers is included in Table C-3 and Figure C-1 which present information about radio listening by location (source: RADAR ® 56, Fall 1997, © Copyright Statistical Research, Inc.).

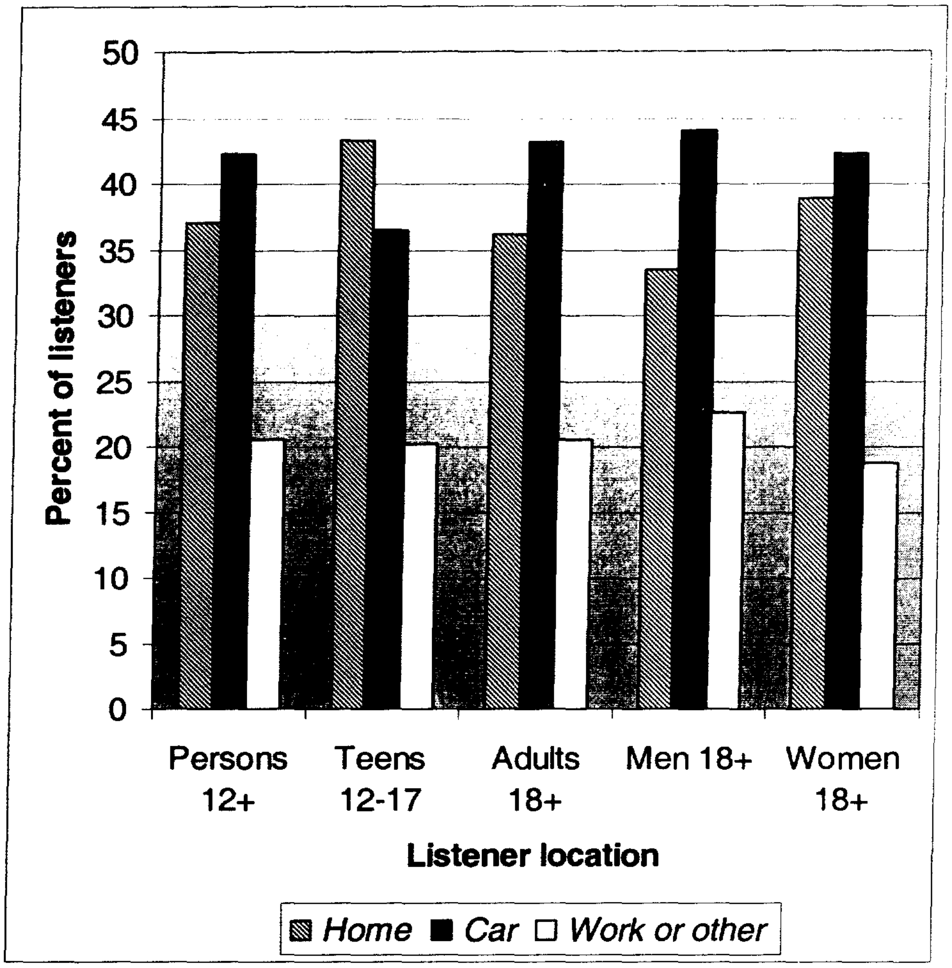
Table C-3. Radio Listening by Location

Weekdays (Monday-Friday, 24 hours)

Source: RADAR ® 56, Fall, 1997 (C) Copyright Statistical Research, Inc.

	PERCENT OF LISTENERS IN...		
	HOME	CAR	WORK OR OTHER
Persons 12+	37.1	42.3	20.6
Teens 12-17	43.3	36.5	20.2
Adults 18+	36.2	43.2	20.6
Men 18+	33.5	44	22.6
Women 18+	38.9	42.3	18.8

Figure C-1. Radio Listening by Location
Weekdays (Monday-Friday, 24 hours)
* *Source: RADAR ® 56, Fall, 1997 (C) Copyright Statistical Research, Inc.*



Appendix D. Test Matrix – Lab Test Guidelines, FM-band Portion

LAB TESTS, FM-BAND PORTION

TEST	DESCRIPTION	AWGN	LINEAR	NON-LINEAR	FADING	INTERFERERS CO-CHAN	1ST-ADJ	2ND-ADJ	COMMENTS
A	**[illegible]**								
1)	Average and peak RF power measurements		✔						
2)	RF spectrum plot		✔						
3)	Digital audio subjective performance baseline	✔	✔						
4)	Baseline characterization of system digital performance	✔	✔						
5)	Analog proof-of-performance test results								
6)	Calibration record of equipment								
B	**IBOC system performance with AWGN**								
1)	Linear channel, no interferers	✔	✔						• Digital audio performance • Data transmission performance
2)	Linear channel, 1st-adjacent channel interference	✔	✔				✔		
3)	Multipath fading channel, no interferers	✔			✔				
4)	Multipath fading channel, 1st-adjacent channel interference	✔			✔		✔		
C	**IBOC system performance with special impairments**								
1)	Impulse noise		✔						• Digital audio performance • Data transmission performance
2)	Impulse noise, 1st-adjacent channel interference		✔				✔		
3)	Narrowband noise		✔						
4)	Narrowband noise, 1st-adjacent channel interference		✔				✔		
5)	Airplane flutter		✔						
6)	Airplane flutter, 1st-adjacent channel interference		✔				✔		
7)	Weak signal		✔						
8)	Weak signal, 1st-adjacent channel interference		✔				✔		
9)	Delay spread/doppler		✔						
10)	Delay spread/doppler, 1st-adjacent channel interference		✔				✔		
D	**IBOC "digital-to-digital" compatibility performance**								
1)	Co-channel interference		✔			✔			• Digital audio performance • Data transmission performance
2)	Single 1st-adjacent channel interference		✔				✔		
3)	Simultaneous upper and lower 1st-adjacent channel interference		✔				✔		
4)	Single 2nd-adjacent channel interference		✔					✔	
5)	Single 2nd-adjacent channel interference w/1st adj. channel interference		✔				✔	✔	

LAB TESTS, FM-BAND PORTION

TEST	DESCRIPTION	AWGN	LINEAR	NON-LINEAR	FADING	INTERFERERS CO-CHAN	1ST-ADJ	2ND-ADJ	COMMENTS
6)	Simultaneous upper and lower 2nd-adjacent channel interference		✔					✔	
7)	Simultaneous upper and lower 2nd-adjacent channel interference with non-linearity			✔				✔	
E	**IBOC "digital-to-digital" compatibility performance in a multipath fading channel**								
1)	Co-channel interference				✔	✔			• Digital audio performance • Data transmission performance
2)	Single 1st-adjacent channel interference				✔		✔		
3)	Simultaneous upper and lower 1st-adjacent channel interference				✔		✔		
4)	Single 2nd-adjacent channel interference				✔			✔	
5)	Single 2nd-adjacent channel interference w/1st adj. channel interference				✔		✔	✔	
6)	Simultaneous upper and lower 2nd-adjacent channel interference				✔			✔	
7)	Simultaneous upper and lower 2nd-adjacent channel interference with non-linearity			✔	✔			✔	
F	**IBOC "digital-to-analog" compatibility performance**								
1)	Co-channel interference		✔			✔			• Analog main channel audio performance
2)	Single 1st-adjacent channel interference		✔				✔		
3)	Simultaneous upper and lower 1st-adjacent channel interference		✔				✔		
4)	Single 2nd-adjacent channel interference		✔					✔	
5)	Single 2nd-adjacent channel interference w/1st adj. channel interference		✔				✔	✔	
6)	Simultaneous upper and lower 2nd-adjacent channel interference		✔					✔	
G	**IBOC "digital-to-analog" compatibility performance in a multipath fading channel**								
1)	Co-channel interference				✔	✔			• Analog main channel audio performance
2)	Single 1st-adjacent channel interference				✔		✔		
3)	Simultaneous upper and lower 1st-adjacent channel interference				✔		✔		
4)	Single 2nd-adjacent channel interference				✔			✔	
5)	Single 2nd-adjacent channel interference w/1st adj. channel interference				✔		✔	✔	

TEST	LAB TESTS, FM-BAND PORTION DESCRIPTION	AWGN	LINEAR	NON-LINEAR	FADING	INTERFERERS CO-CHAN	1ST-ADJ	2ND-ADJ	COMMENTS
6)	Simultaneous upper and lower 2nd-adjacent channel interference				✔			✔	
H	**IBOC "digital-to-digital" compatibility performance**								
1)	Single 1st-adjacent channel interference		✔				✔		• Digital audio performance • Data transmission performance
2)	Simultaneous upper and lower 1st-adjacent channel interference		✔				✔		
3)	Single 2nd-adjacent channel interference		✔					✔	
I	**IBOC digital-to-digital compatibility performance in a multipath fading channel**								
1)	Single 1st-adjacent channel interference				✔		✔		• Digital audio performance • Data transmission performance
2)	Simultaneous upper and lower 1st-adjacent channel interference				✔		✔		
3)	Single 2nd-adjacent channel interference				✔			✔	
4)	Simultaneous upper and lower 2nd-adjacent channel interference				✔			✔	
J	**IBOC acquisition/re-acquisition performance**								
1)	Short interruption, linear channel		✔						• Acquisition / re-acquisition performance
2)	Long interruption , linear channel		✔						
3)	Short interruption, linear channel, AWGN	✔	✔						
4)	Long interruption, linear channel, AWGN	✔	✔						
5)	Short interruption, linear channel, 1st-adj. channel interference		✔				✔		
6)	Long interruption, linear channel, 1st-adj. channel interference		✔				✔		
7)	Short interruption, fading channel				✔				
8)	Long interruption, fading channel				✔				
9)	Short interruption, AWGN, fading channel	✔			✔				
10)	Long interruption, AWGN, fading channel	✔			✔				
11)	Short interruption, fading channel, 1st-adj. channel interference				✔		✔		
12)	Long interruption, fading channel, 1st-adj. channel interference				✔		✔		
K	**DAB quality**								
1)	Subjective assessment report of unimpaired IBOC audio quality (linear channel) versus analog FM		✔						• Suggested source and reference audio available from NRSC
2)	"Long-form" DAT through IBOC system		✔						• See Sect. 4.2

LAB TESTS, FM-BAND PORTION

TEST	DESCRIPTION	AWGN	LINEAR	NON-LINEAR	FADING	INTERFERERS: CO-CHAN	INTERFERERS: 1ST-ADJ	INTERFERERS: 2ND-ADJ	COMMENTS
[illegible]	[illegible]								
1)	Host analog main channel audio performance versus presence or absence of IBOC digital signal energy		✔						• Host analog main channel audio performance • Host subcarrier performance
2)	Host analog main channel audio performance versus presence or absence of IBOC digital signal energy				✔				
3)	Host subcarrier audio and/or data performance versus presence or absence of IBOC digital signal energy		✔						
4)	Host subcarrier audio and/or data performance versus presence or absence of IBOC digital signal energy				✔				
M	**IBOC "host analog-to-digital" compatibility performance**								
1)	Digital audio, data transmission performance versus percent modulation of analog host signal		✔						• Digital audio performance • Data transmission performance
2)	Digital audio, data transmission performance versus percent modulation of analog host signal				✔				

Appendix E. Test Matrix – Lab Test Guidelines, AM-band Portion

LAB TESTS, AM-BAND PORTION

TEST	DESCRIPTION	AWGN	LINEAR			INTERFERERS CO-CHAN	1ST-ADJ	2ND-ADJ	3RD-ADJ	COMMENTS
A	**System calibration**									
1)	Average and peak RF power measurements		✔							
2)	RF spectrum plot		✔							
3)	Digital audio subjective performance baseline	✔	✔							
4)	Baseline characterization of system digital performance	✔	✔							
5)	Analog proof-of-performance test results									
6)	Calibration record of equipment									
B	**IBOC system performance with AWGN**									
1)	Linear channel, no interferers	✔	✔							• Digital audio performance • Data transmission performance
C	**IBOC system performance with special impairments**									
1)	Impulse noise		✔							• Digital audio performance • Data transmission performance
2)	Weak signal		✔							
D	**IBOC "digital-to-digital" compatibility performance**									
1)	Co-channel interference		✔			✔				• Digital audio performance • Data transmission performance
2)	Single 1st-adjacent channel interference		✔				✔			
3)	Simultaneous upper and lower 1st-adjacent channel interference		✔				✔			
4)	Single 2nd-adjacent channel interference		✔					✔		
5)	Simultaneous upper and lower 2nd-adjacent channel interference		✔					✔		
6)	Single3rd-adjacent channel interference								✔	
F	**IBOC "digital-to-analog" compatibility performance**									
1)	Co-channel interference		✔			✔				• Analog main channel audio performance
2)	Single 1st-adjacent channel interference		✔				✔			
3)	Single 2nd-adjacent channel interference		✔					✔		

LAB TESTS, AM-BAND PORTION

TEST	DESCRIPTION	AWGN	LINEAR			INTERFERERS CO-CHAN	1ST-ADJ	2ND-ADJ	3RD-ADJ	COMMENTS
H	**IBOC "digital-to-digital" compatibility performance**									
1)	Co-channel interference					✔				• Digital audio performance • Data transmission performance
2)	Single 1st-adjacent channel interference		✔				✔			
3)	Simultaneous upper and lower 1st-adjacent channel interference		✔				✔			
4)	Single 2nd-adjacent channel interference									
3)	Simultaneous upper and lower 2nd-adjacent channel interference		✔					✔		
J	**[illegible] acquisition performance**									
1)	Short interruption, linear channel		✔							• Acquisition / re-acquisition performance
2)	Long interruption , linear channel		✔							
3)	Short interruption, linear channel, AWGN	✔	✔							
4)	Long interruption, linear channel, AWGN	✔	✔							
K	**DAB quality**									
1)	Subjective assessment report of unimpaired IBOC audio quality (linear channel) versus analog AM (and optionally, analog FM)		✔							• Suggested source and reference audio available from NRSC
2)	"Long form" DAT through IBOC system		✔							• See Sect. 4.2
L	**IBOC "digital-to-host analog" compatibility performance**									
1)	Host analog main channel audio performance versus presence or absence of IBOC digital signal energy		✔							• Host analog main channel audio performance
M	**IBOC "host analog-to-digital" compatibility performance**									
1)	Digital audio, data transmission performance versus percent modulation of analog host signal		✔							• Digital audio performance • Data transmission performance

Appendix F. DAB Subcommittee Goals & Objectives

CEMA
Consumer Electronics
Manufacturers Association
A sector of the EIA

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(703) 907-7500
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NATIONAL RADIO SYSTEMS COMMITTEE

National Association of
NAB
BROADCASTERS

1771 N Street, NW
Washington, DC 20036-2891
(202) 429-5339
FAX (202) 775-4981

5/14/98

DAB Subcommittee

Goals & Objectives

(as adopted by the Subcommittee on May 14, 1998)

Objectives

(a) To study IBOC DAB systems and determine if they provide broadcasters and users with:

- A digital signal with significantly greater quality and durability than available from the AM and FM analog systems that presently exist in the United States;
- A digital service area that is at least equivalent to the host station's analog service area while simultaneously providing suitable protection in co-channel and adjacent channel situations;
- A smooth transition from analog to digital services.

(b) To provide broadcasters and receiver manufacturers with the information they need to make an informed decision on the future of digital audio broadcasting in the United States, and if appropriate to foster its implementation.

Goals

To meet its objectives, the Subcommittee will work towards achieving the following goals:

(a) To develop a technical record and, where applicable, draw conclusions that will be useful to the NRSC in the evaluation of IBOC systems;

(b) To provide a direct comparison between IBOC DAB and existing analog broadcasting systems, and between an IBOC signal and its host analog signal, over a wide variation of terrain and under adverse propagation conditions that could be expected to be found throughout the United States;

(c) To fully assess the impact of the IBOC DAB signal upon the existing analog broadcast signals with which they must co-exist;

(d) To develop a testing process and measurement criteria that will produce conclusive, believable and acceptable results, and be of a streamlined nature so as not to impede rapid development of this new technology;

(e) To work closely with IBOC system proponents in the development of their laboratory and field test plans, which will be used to provide the basis for the comparisons mentioned in Goals (a) and (b);

(f) To indirectly participate in the test process, by assisting in selection of (one or more) independent testing agencies, or by closely observing proponent-conducted tests, to insure that the testing as defined under Goal (e) is executed in a thorough, fair and impartial manner.

Appendix G. IBOC Status Report (6/98)

"*In-band/on-channel (IBOC) DAB – a Status Report*," published in the proceedings of the 1998 Radio Montreux Conference.

In-band/on-channel (IBOC) DAB - a Status Report

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ABSTRACT

In-band/on-channel (IBOC) Digital Audio Broadcasting (DAB) is the preferred approach for introduction of terrestrial DAB services in the U.S. given the lack of spectrum availability for implementation of a new-band system (such as Eureka-147). Discussed in this article are some of the test results obtained by the EIA/NRSC DAB test lab, in the 1994-96 time frame, on "first-generation" AM and FM IBOC systems, followed by an overview of the "next-generation" IBOC systems currently being developed, in particular, the differences between first and next generation systems which are expected to result in significantly improved performance.

INTRODUCTION

Audio program broadcasting, traditionally an analog service utilizing either AM or FM modulation, is rapidly evolving to digital methods. Digital Audio Broadcasting (DAB) promises to bring to listeners an audio signal with vastly improved characteristics, accompanied by additional digital data-based services not presently available from the analog signals now in use.

Currently, the predominant form of DAB being implemented around the world is based on the Eureka-147 standard [19]. Since each Eureka-147 signal is approximately 1.5 MHz wide (accommodating multiple audio programs and/or other data services per signal) it is not possible to incorporate the Eureka-147 system into the existing AM and FM broadcasting bands (from 535 to 1705 kHz, and 88 to 108 MHz, respectively), but instead, new spectrum must be allocated for their use, and hence Eureka-147 is sometimes referred to as a "new band" service, referring to the new frequency band it requires (with respect to the "existing" radio broadcast bands) for implementation.

In 1992, the ITU-R instituted worldwide allocations for DAB services, which were primarily in the L-band (1452-1492 MHz) and the S-band (2310-2360 MHz in the U.S., and 2535-2655 in parts of Asia and Europe). Many Administrations have made use of these allocations to initiate DAB service; in the U.S., two Satellite Digital Audio Radio Service (SDARS) providers have each been granted licenses for 12.5 MHz portions of the U.S. S-band DAB allocation (25 MHz total bandwidth) and expect to begin transmissions to subscribers in late 1999/early 2000.

However, there are no frequencies available in the U.S. for the implementation of a new-band terrestrial DAB service, and consequently U.S. broadcasters are paying close attention to the on-going development of DAB systems which are designed to be used in the existing broadcast bands and are compatible with the analog signals currently in use. These systems are referred to as "in-band/on-channel" (IBOC) and are being designed and tested for both the AM and FM bands by a number of proponents.

Designing a viable IBOC system has proven to be a formidable challenge—the approach has typically been to take advantage of the un-used portion of the spectrum for the AM or FM service which is in the immediate vicinity of the analog carrier (as defined by the service frequency allocation "mask"), or to implement frequency re-use by including an additional carrier (or carriers) in quadrature to the existing analog carrier. In either case, the analog signals are in close proximity to the digital signals and great care must be exercised to prevent unwanted interference between them. Clearly this is a much more difficult task than that faced by the designers of new-band systems, who assume a relatively benign environment (from an interference standpoint) populated by carriers of the same type and with sufficient bandwidth for transmission.

The purpose of this paper is to summarize the current status of IBOC DAB system development. First, a brief review of some early "1st-generation" systems and their performance, as determined by an independent testing program, will be given. Then, a discussion of "next generation" system design is provided, with an emphasis on how these next generation systems address the problems observed in the 1st-generation. Also included is a list of references

As presented at Radio Montreux, 10-13 June 1998, Montreux, Switzerland

which encompass the treatment of IBOC systems in both technical and trade publications.

FIRST-GENERATION SYSTEMS

A series of laboratory and field tests were conducted by the Electronic Industries Association (EIA) and the National Radio Systems Committee (NRSC, an industry standards organization co-sponsored by the EIA and the NAB) during the 1994-96 time period [see references 4, 5, 6, 11, 16, and 20 for background information and test results] on a number of DAB systems (listed in Table 1). Of those systems participating, four were of the IBOC type (three FM, one AM); some of the more interesting test results obtained for these systems will be given below.

Table 1. Systems Participating in EIA/NRSC DAB Tests

SYSTEM	TYPE/BAND	LAB	FIELD
Eureka-147	New-band terrestrial / L-band	✓	✓
VOA/JPL	Satellite/S-band	✓	✓
AT&T/Lucent	IBAC/FM-band	✓	✓
AT&T/Lucent/Amati	IBOC/FM-band	✓	
USADR FM-1	IBOC/FM-band	✓	
USADR FM-2	IBOC/FM-band	✓	
USADR AM	IBOC/AM band	✓	

The spectral shape and occupancy of the four tested IBOC systems is illustrated in Figure 1 through Figure 5. Note that there were two operating modes for the AT&T/Lucent/Amati* system—double sideband (DSB) and lower sideband (LSB). Characteristics of these systems, and in addition, characteristics of the next generation systems to be discussed below, are given in Table 2 and Table 3.

All four of these 1st-generation IBOC systems were shown (by the EIA/NRSC tests) to be unsuitable for deployment as viable DAB systems, for various reasons. In spite of this overall result, all four systems did demonstrate excellent audio quality in an unimpaired environment [8] (also refer to [9] for analysis of audio quality in an impaired environment), and an evaluation done by one of the proponents (after

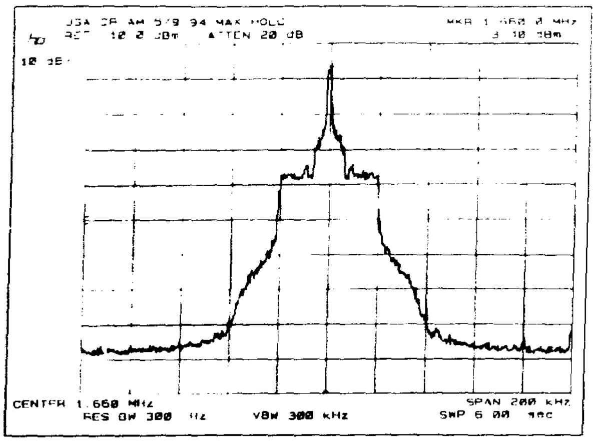

Figure 1. USADR AM IBOC Spectrum Plot

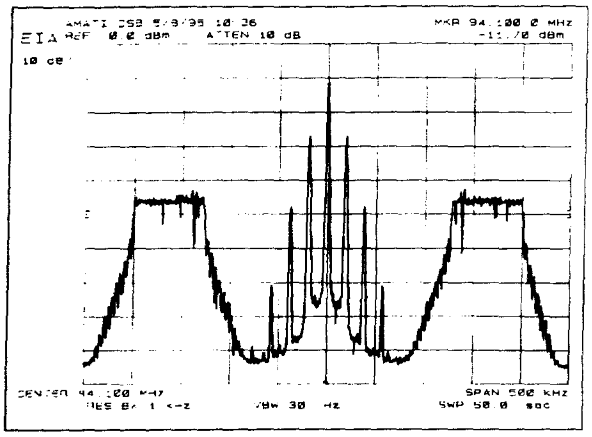

Figure 2. AT&T/Amati FM IBOC (DSB) Spectrum Plot

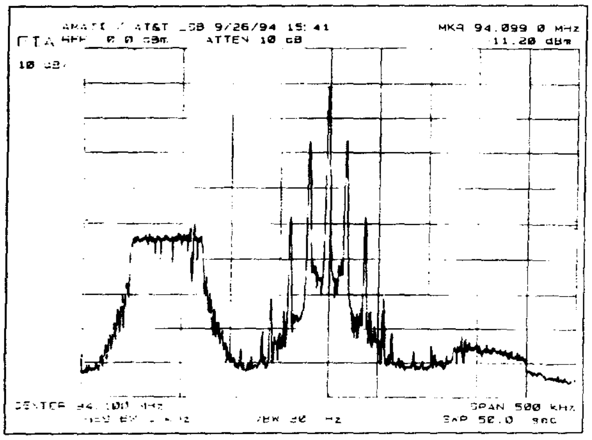

Figure 3. AT&T/Amati FM IBOC (LSB) Spectrum Plot

*These systems were originally referred to as "AT&T/Amati" but this designation was expanded to "AT&T/Lucent/Amati" following the divestiture by AT&T of Lucent Technologies. Within this report, and in many of the references cited herein, both designations are used interchangeably.

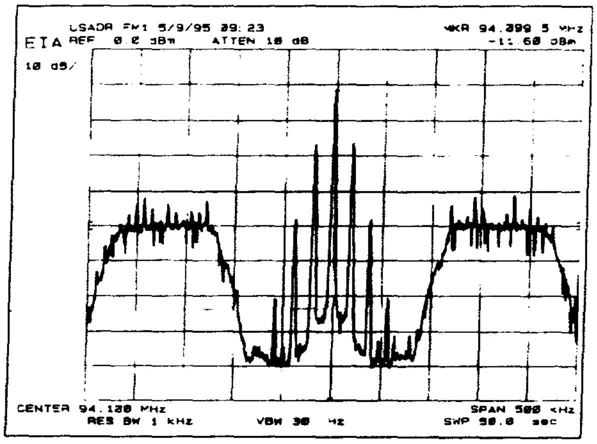

Figure 4. USADR FM-1 IBOC Spectrum Plot

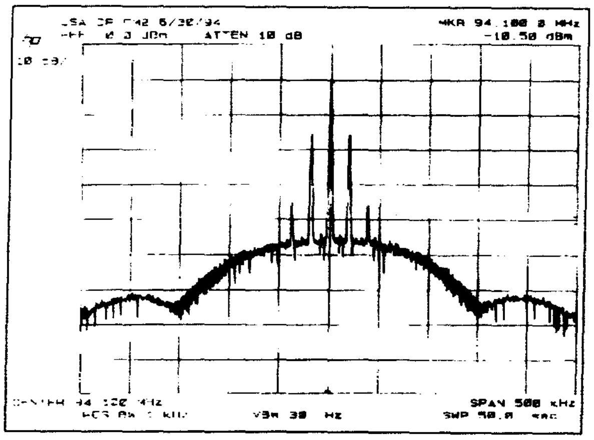

Figure 5. USADR FM-2 IBOC Spectrum Plot

testing was complete), USA Digital Radio, Inc.† (USADR), on their IBOC systems as well as the corresponding test data, concluded that the IBOC concept was valid, again, in spite of the EIA/NRSC test results [14].

One of the more discouraging results for the 1st-generation FM IBOC systems involved what is referred to as "digital-to-digital" compatibility. Shown in Figure 6 is the digital-to-digital compatibility of the four FM systems (at "Threshold of Audibility" or TOA). In these tests, for each of the three interference scenarios shown, the signal level of the IBOC interferer was increased until audible interference was just detectable in the digital audio output of the desired IBOC signal (this is the definition of TOA). In the figure, the y-axis value for each case illustrates to what extent the measured performance exceeded, or failed to meet, the interference contour values specified by the FCC for short-spaced FM stations (U.S. CFR §73.215) which must currently be met for analog service.

Table 2. AM IBOC Comparison of System Parameters (USA Digital Radio)

PARAMETER	1ST-GENERATION SYSTEM	NEXT-GENERATION SYSTEM
RF bandwidth	40 kHz	30 kHz
Audio coding rate	96 kbps	48 / 32 / 16 kbps
Channel coding	Rate 3/4 FEC	Under development
Channel bit rate	128 kbps	Approx. 96 kbps

Note: Information regarding Digital Radio Express' AM IBOC system was not yet available at the time of writing this article.

In other words, the FCC specifies the allowable D/U ratio for interferers at the protected contour of the desired station. For co-channel interferers, this value is 20 dB; for 1st- and 2nd-adjacent interferers, the corresponding values are 6 dB and -40 dB. Ideally, the interference caused by a co- or adjacent-channel IBOC signal would not be audible within the desired station's protected contour. So, for a given case, if the D/U ratio measured at the TOA is *higher* than the FCC-specified value, this means that this interference would be noticeable within the protected contour of the desired station. Conversely, if the measured D/U ratio is *lower* than the FCC's value, then the effect of the interference would not be felt inside the protected contour.

For example, the data point shown in Figure 6 for AT&T/Amati (DSB), co-channel, is approximately 10 dB - this means that the measured D/U ratio for TOA, for this case, was 10 dB *lower* than the D/U specified by the FCC, and therefore the effect of the IBOC co-channel interferer on the desired IBOC signal would not be noticed within its protected contour. For the 1st-adjacent channel data point, again for the AT&T/Amati DSB system, Figure 6 indicates a margin of approximately minus 20 dB - this means that the measured D/U ratio was 20 dB *higher* than the FCC requirement for this case, resulting presumably in detectable interference due to the 1st- adjacent channel, within the protected contour of the desired IBOC station.

The poor 2nd-adjacent channel performance shown in Figure 6 is due to the fact that the IBOC sidebands (as illustrated in Figures 1-5) are actually

† USADR is a partnership of Westinghouse and Gannet Company, Inc. (Westinghouse represents the combination of Group W, CBS Radio, Infinity Broadcasting, and Westinghouse Electric).

overlapping for 2nd-adjacent carriers. This is one of the problems with these 1st-generation systems that has been addressed in the next-generation implementations, and will be discussed in more detail in the next section.

In the next two figures, the results from some of the FM IBOC " digital - to - analog " compatibility tests are presented. These tests were repeated for each of five different, commercially available FM receivers, to establish the impact of the IBOC digital signal on *analog* receiver performance. As is demonstrated by the results, receivers with narrower IF filters, better able to reject the IBOC signal energy, did significantly better than those with wider IFs.

Figure 7 shows how the IBOC signal affects its "host", for the 5 different receivers tested. For the host compatibility test, for each receiver, the main channel audio signal-to-noise ratio was measured *first* with the IBOC signal turned off, to establish the receiver's baseline performance—these figures are shown as the

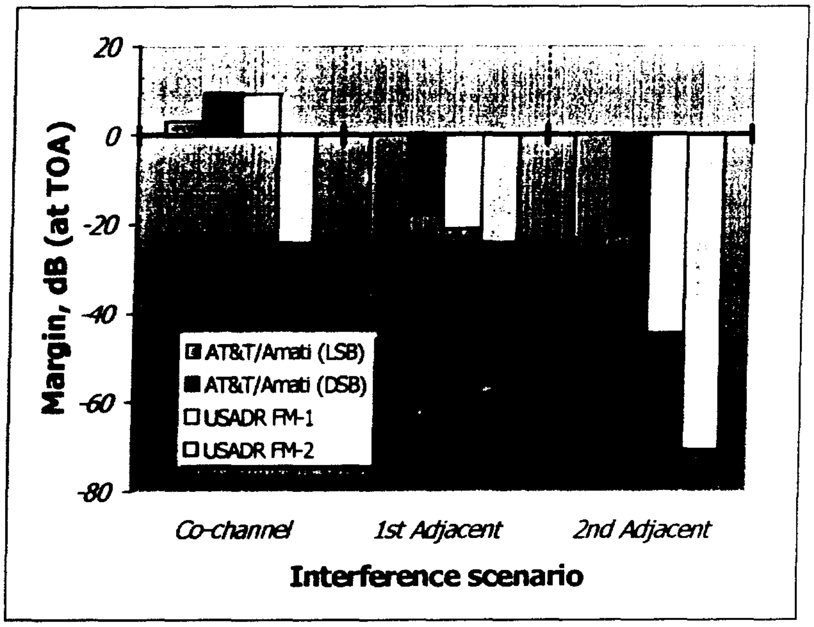

Figure 6. FM IBOC Digital-to-digital Compatibility

Table 3. Comparison of FM IBOCSystem Parameters

	1ST-GENERATION SYSTEMS				NEXT-GENERATION SYSTEMS	
PARAMETER	**AT&T/AMATI (DSB)**	**AT&T/AMATI (LSB)**	**USADR-FM1**	**USADR-FM2**	**USA DIGITAL RADIO**	**DIGITAL RADIO EXPRESS**
Diversity	None	None	None	None	Time and Frequency	Time and Frequency
Simulcast with analog?	No	No	No	No	Yes	Optional
Audio coding rate	160 kbps	128 kbps	128-256 kbps (variable)	128-256 kbps (variable)	96 kbps	128 kbps
Audio coding technique	PAC	PAC	Musicam	Musicam	PAC	MPEG2-AAC
Channel bit rate	264 kbps	216 kbps	392 kbps	384 kbps	240 kbps	256 kbps[1]
Channel coding	Reed-Solomon	Reed-Solomon	Concatenated code (variable rate)	Concatenated code (variable rate)	CPC[2]	Concatenated (Trellis outer, block inner)
Modulation technique	DMT[3]	DMT	Multicarrier/ CDM	Multicarrier/ CDM (w/freq. slide)	OFDM	OFDM
RF bandwidth[4]	150 kHz	75 kHz	200 kHz	400 kHz	134 kHz	140 kHz
Data capacity	<15 kbps	<15 kbps	<64 kbps	<64 kbps	>64 kbps	>64 kbps[1]

Notes:

(1) Estimated; exact figures not yet disclosed;

(2) CPC is an acronym for Complementary Punctured Code; additional information on this technique may be found in [13];

(3) DMT is an acronym for Discrete Multitone, a form of orthogonal frequency division multiplexing developed by the Amati Corporation;

(4) Figures for RF bandwidth represent bandwidth of digital signal components only and do not include bandwidth of accompanying analog signal.

bottom bar in each group. Then, the measurement was repeated with the IBOC signal turned on, resulting in the performance shown.

Notice how receiver-dependent these results are—in particular, for the two automotive receiver tested, the Delco and the Ford, the presence of the IBOC signal had little or no effect on the host audio. On the other hand, for the Pioneer receiver we see significant degradation, on the order of 30 dB. This difference is believed to be due to the different IF bandwidths used in these receivers, with the narrow-IF automotive receivers successfully rejecting the IBOC signal energy and hence showing little effect from the presence of the IBOC signal.

In Figure 8, the results for the 1st-adjacent channel interferer case are shown. Those receivers with wide IFs—the Denon, Panasonic, and Pioneer—show less degradation due to the presence of the IBOC signal, suggesting that this performance is dominated by the analog (as opposed to the digital) component of the 1st-adjacent interferer, which, of course, is not being rejected sufficiently due to the wide IF.

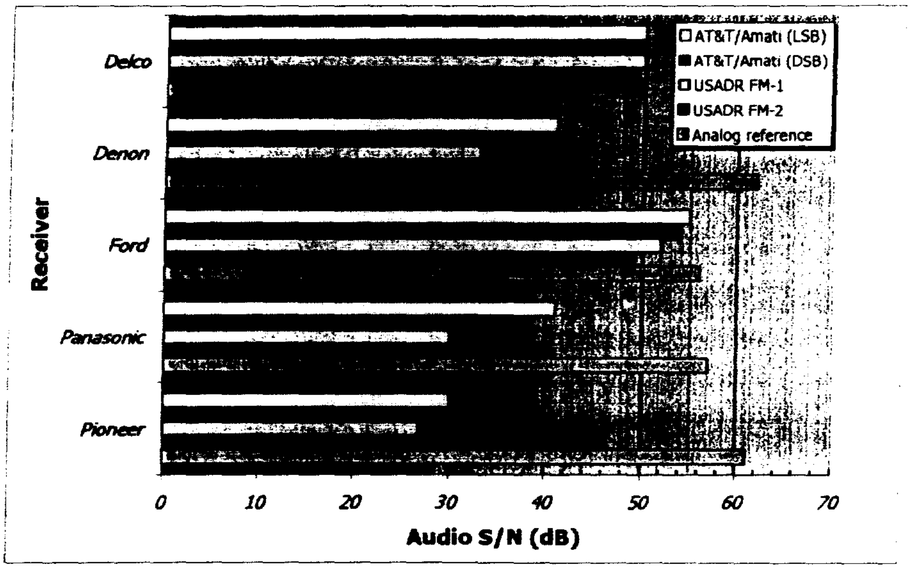

Figure 7. FM IBOC Digital-to-Analog Compatibility - Interference to Analog Host

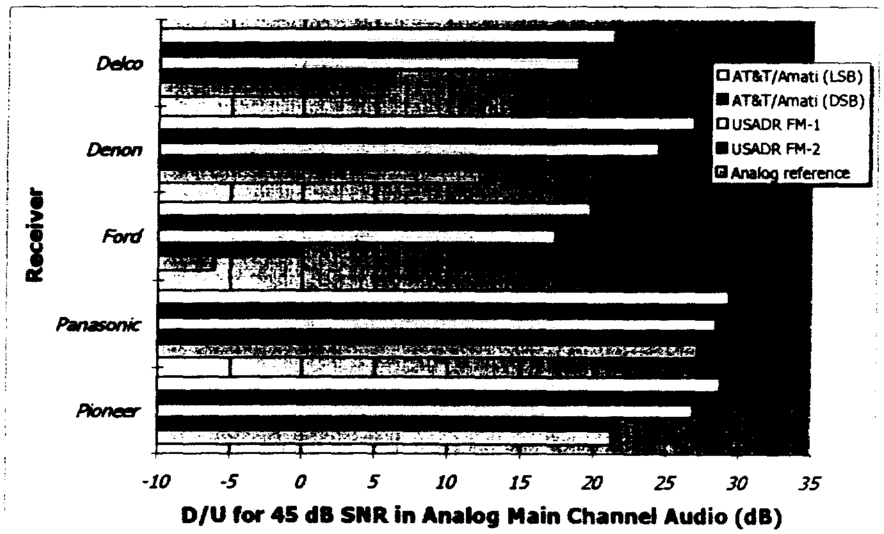

Figure 8. FM IBOC Digital-to-Analog Compatibility - Interference due to 1st-Adjacent Channel

The automotive receiver performance, on the other hand, indicates significant degradation due to the IBOC signal, especially for the Ford receiver. With the narrow IF filter of the automotive receiver in mind, it is understandable why the performance in the *reference* case is so good. However, this filter cannot reject all of the digital signal in the 1st-adjacent channel interferer, since the digital signal of the *interferer* is effectively "co-channel" to the *desired* analog signal. The narrow IF filter is probably rejecting some of the interferers digital energy, though, since the automotive receiver performance with IBOC (in this 1st-adjacent case) is still the best of all the receivers tested.

Another parameter of interest measured in the EIA/NRSC tests was the amount of time it took each system to initially acquire its signal, i.e. "acquisition time." These results are presented, for the FM IBOC systems, in Figure 9, along with the measured performance of the Eureka-147 system, included for sake of comparison. The three data points recorded for each system are referenced to the system "point of failure" (POF) which, for this test, was defined as the point where the receiver lost lock due to weak signal level. The data for "POF-2 dB" represents the acquisition time of the system when the receiver input level was set 2 dB higher than the level at POF, etc.

The final result to be presented here pertains to the sole AM IBOC system's host analog compatibility performance. As was true in the FM case, the AM IBOC signal is degrading the host analog S/N ratio, by the amounts shown in Figure 10, for four different receiver / bandwidth combinations. Only 2 bars per receiver are shown, with the analog reference bar on bottom, and the USADR AM IBOC system result above that.

This performance indicates that the digital sidebands of the AM signal are significantly increasing the noise of the analog audio signal. Notice how, in the case of the Denon receiver, narrowing the IF filter improves the analog signal's S/N ratio when the IBOC signal is present, but has no effect in the reference case, suggesting that the IBOC signal energy is responsible for the observed degradation.

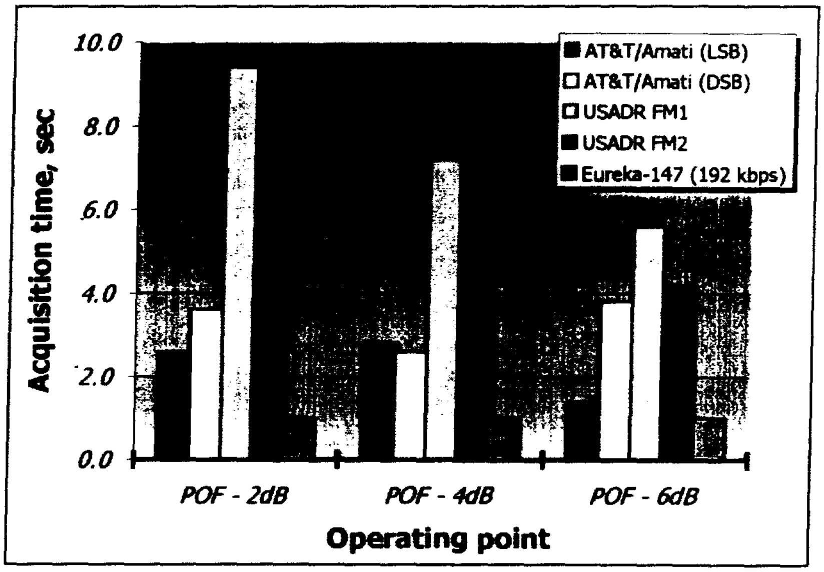

Figure 9. FM IBOC Acquisition Time Measurements

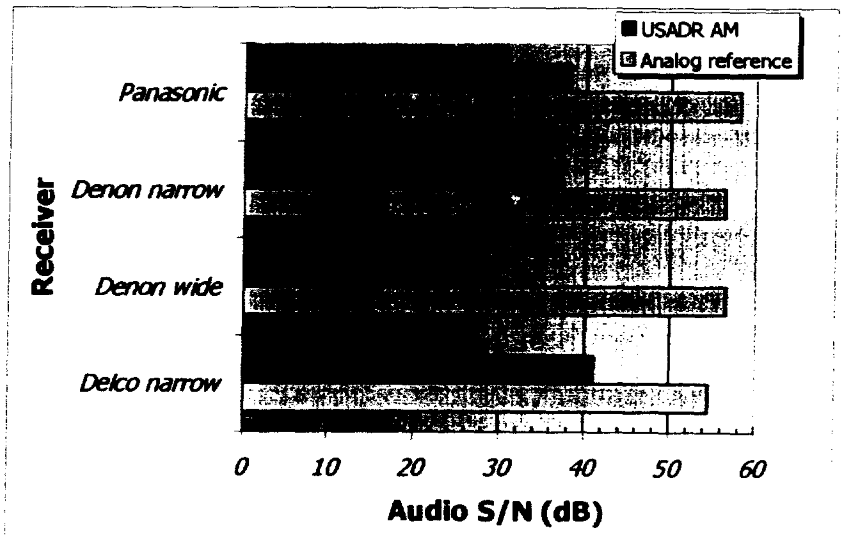

Figure 10. AM IBOC Interference to Analog Host

After these tests were concluded, there appeared to be a reduced amount of activity in the pursuit of IBOC solutions for DAB. In September of 1996, the NRSC's DAB Subcommittee, which was responsible for directing the NRSC's involvement in the test program, suspended its activities until such time as an IBOC system (or systems) which seemed viable could be identified. At about that same time, a paper was delivered at the 1996 Society of Broadcast Engineering Conference by USADR [12] discussing possible improvements to their FM IBOC system. There was no corresponding work being done by the other early FM IBOC proponent, AT&T / Lucent / Amati, and up to the time of the preparation of this article (April 1998) they have not reappeared as an active IBOC proponent (although AT&T and Lucent, separately and neither in conjunction with Amati, have been involved in ongoing IBOC development).

Also, during the concluding period of the EIA/NRSC tests, there was some activity surrounding an FM-subcarrier based approach to DAB by "FM Digital," a partnership of Sanders, a Lockheed Martin Company, and a U.S. broadcaster, WCRB-FM. This approach involved the use of a digital FM subcarrier with a 200 kbit/sec data capacity, and was demonstrated in prototype form at the 1996 NAB convention in Las Vegas, NV, along with an accompanying technical presentation at the 1996 NAB Broadcast Engineering Conference [18]. Although additional work was performed to develop this system, the partnership was dissolved in December of 1997 and this effort was apparently abandoned.

NEXT-GENERATION SYSTEMS

1997 proved to be a key year in the development of the next generation of IBOC systems. Beginning with the 1997 NAB convention, USADR and its affiliated organizations—Xetron, of Cincinnati, OH, working on the AM IBOC development; Westinghouse Wireless Solutions, of Linthicum, MD, focusing on program management and FM IBOC design; and Lucent Technologies, Murray Hill, NJ (who had earlier been in "competition" with USADR), involved in audio coding design and IBOC "all-digital" systems—released a number of technical papers [7, 10, 13-15] which described new techniques for IBOC signal processing and "breakthroughs" which they felt would greatly improve upon the performance of their first-generation systems.

These papers were accompanied by exhibits at both the 1997 NAB convention (in April) and The NAB Radio Show (in October 1997), as well as "focus group" meetings and a number of engineering "open house" demonstrations for the broadcasting industry, at the development facilities in Cincinnati, OH (Xetron), and Linthicum, MD (Westinghouse Wireless Solutions), demonstrating the strides being made and the level of effort being expended in AM and FM IBOC system development.

Also in 1997, a totally new IBOC system proponent emerged—Digital Radio Express (DRE), San Jose, CA [17]—with a prototype FM IBOC system apparently ready for test in early 1998, in hardware prototype form, and plans to roll out an AM IBOC system in mid-1998 also in hardware form and ready for test. DRE has as a prime investor a major semiconductor manufacturer, TriTech Semiconductor, and expects to have its FM IBOC receiver design (shown in prototype form in Figure 11) reduced to a single IC which will be easily incorporated into existing receiver designs, according to DRE.

As a consequence of these developments, the NRSC's DAB Subcommittee was re-activated in January 1998, and is currently working on a generic test plan for use by IBOC system developers, which will allow for a thorough evaluation of developing IBOC technology.

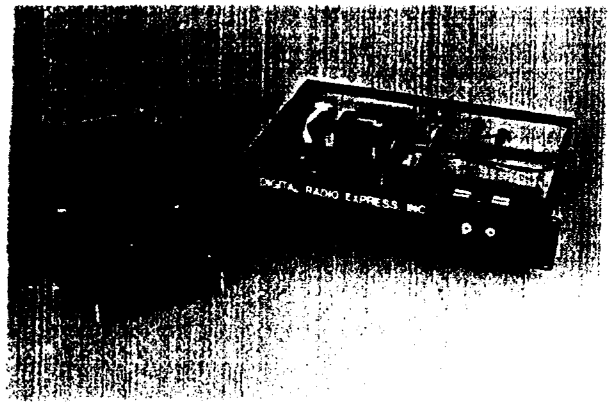

Figure 11. DRE FM IBOC Prototype Hardware - receiver (card, on left) and exciter (right)

In the remaining part of this section, some of the specific aspects of these next-generation IBOC systems, in particular those expected to make them viable technologies, will be discussed. Interested readers are directed towards the numerous articles which exist on these systems for more complete information on the details of their design (see "References" section below). It is important to note that at the time this article was written (April 1998), none of these systems had undergone testing, either in the laboratory or field, and consequently their actual performance had not yet been demonstrated. The discussion on design specifics which follows is based on analysis and computer simulations done by the proponents, and it has yet to be conclusively demonstrated that these designs achieve the intended results.

Audio Coding

Many of the compatibility problems encountered in the first-generation IBOC systems were a direct consequence of the spectral occupancy of those systems, which is proportional to the amount of data which needs to be transmitted. Advances made in audio coding technology, since the development of the early IBOC systems, have allowed the design of the next-generation USADR systems, as well as the new DRE systems, to obtain the sought-after audio quality in significantly less bandwidth than that used for the systems tested by EIA/NRSC. This can be seen by comparing the RF bandwidth values provided in Tables 2 and 3 (for 1st- and next-generation systems).

Specifically, USADR is now planning to use an audio coding algorithm known as PAC (for Perceptual Audio Coding, developed by Lucent) for both its AM and FM systems. The FM system will use PAC operating at 96 kbps, while the AM system will use PAC operating from 16 kbps to 48 kbps; in each case, these represent significant reductions in bit rate which ultimately results in reduced spectral occupancy.

DRE has indicated it will use a new technique, recently standardized by the Moving Pictures Expert Group (MPEG) as MPEG2-AAC, operating at 128 kbps, for digital audio transmitted by their FM IBOC system [2] (details on the coding for DRE's AM system have not been announced, but it is assumed that MPEG2-AAC will be adopted for that system, as well, but operating at less than 128 kbps).

Signal Compatibility

The FM IBOC systems under development by USADR and DRE, while different in many aspects, appear similar when observed strictly from a spectral occupancy standpoint. Both systems utilize Orthogonal Frequency Division Multiplexed (OFDM) carriers, grouped into what are called upper and lower sidebands, as shown in Figure 12.

OFDM (also chosen for use in the Eureka-147 system) is a *multi-carrier* modulation technique, that is, the digital bit stream to be modulated is sub-divided into many parallel bit streams, each with a lower bit rate than the original, and these lower-rate bit streams are modulated onto multiple carrier signals (using conventional techniques such as quadrature or eight phase-shift keying) optimally spaced to minimize interference with one another. OFDM signals have a number of advantages over single-carrier modulation techniques, especially in high-interference and multipath fading environments.

These OFDM sidebands, for each system, are independent in that the complete loss of one sideband does not result in system failure, but rather, high-quality digital audio is still achievable given only a single received sideband. (Each system achieves this in a different manner which will be briefly described in the section below entitled "Frequency Diversity").

Sideband independence is just one difference between these new systems and those of the first generation (which also used digital sidebands placed beneath the FM mask). Because lower bit rates are now being used for the digital audio datastreams, it has been possible to make the sidebands narrower than before, which should help to alleviate the compatibility problems encountered with the earlier system designs. In particular:

- The sidebands are constrained to frequencies higher than ±(114+15) kHz above the channel center frequency (as shown in Figure 12) - this is expected to improve compatibility of the IBOC signal to the analog host, which in the earlier systems was being compromised by IBOC digital energy around 114 kHz being translated into the received analog main channel stereo audio signal (114 kHz is the third harmonic of 38 kHz, which is the analog stereo audio L-R subcarrier center frequency);

- On the high side, the sidebands are constrained to frequencies below approximately ±200 kHz (see Figure 12) which should eliminate the 2nd-adjacent channel digital-to-digital compatibility problem discussed earlier. This is illustrated graphically in Figure 13, where it is clear that, for 2nd-adjacent channels, the IBOC sidebands do not overlap (not true for 1st-generation systems).

Spectral occupancy of USADR's next-generation AM system has also been reduced from its original value—this new spectrum is illustrated graphically in Figure 14. As with FM IBOC, OFDM modulation is utilized on the digital portion of the AM IBOC

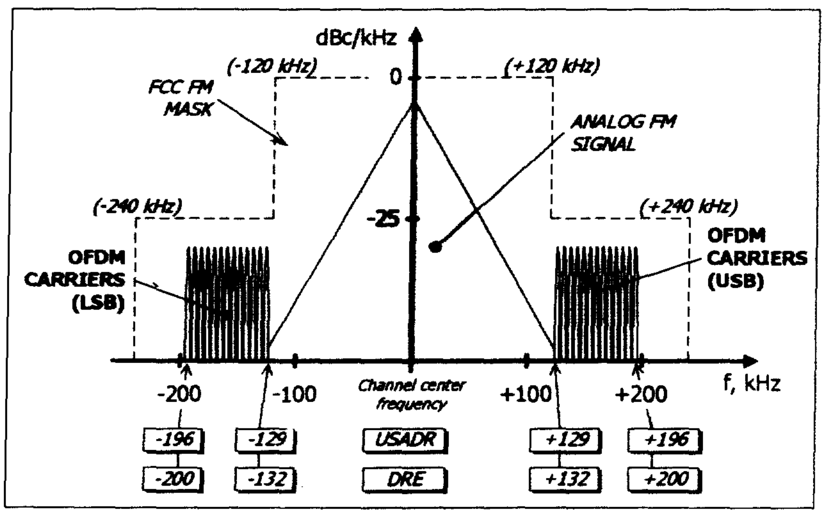

Figure 12. FM IBOC Spectra - Next-generation Systems

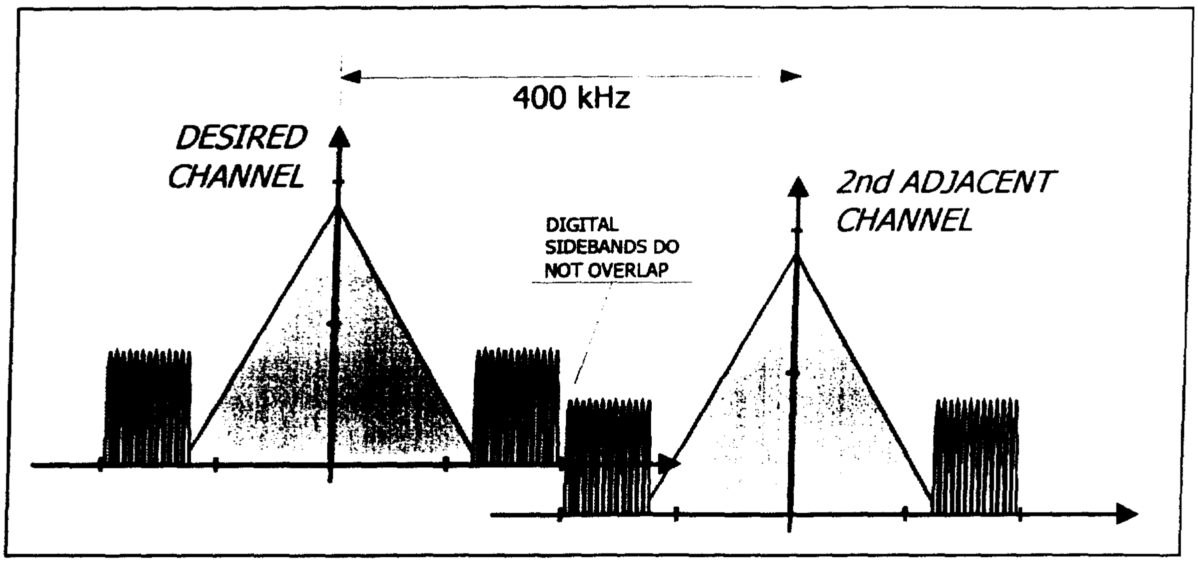

Figure 13. Illustration of 2nd Adjacent Channel Interference for Next-generation FM IBOC

signal. In USADR's AM IBOC system, approximately 70 individual carriers are used, equally spaced across a 30 kHz bandwidth centered on the AM channel center frequency. The data is modulated onto these carriers using one of three techniques - BPSK, 8PSK, or 32QAM - depending upon their location within the channel.

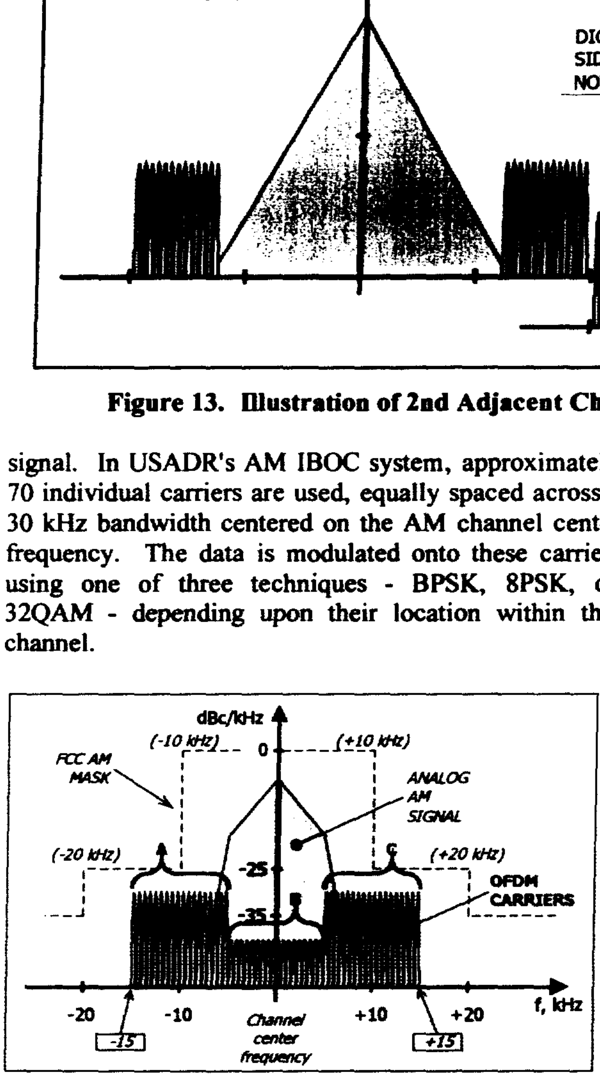

Figure 14. USADR AM IBOC Spectrum - Next-generation System

The digital portion of the spectrum is divided into three separate regions, marked "A," "B," and "C" in the figure, with each region using OFDM modulation. The broadcaster has a great deal of flexibility in how each of these segments are used, but fundamentally the idea is that each of these segments can be processed in the receiver independently such that if one or two segments are unusable (due to, for example, the presence of an adjacent signal), digital audio can be successfully recovered from the surviving segment.

A typical situation in which this would be useful is shown in Figure 15, where desired and 2nd-adjacent AM carriers are depicted. Clearly, segment "C" from the desired channel is interfered with by segment "A" of the 2nd adjacent channel, however, the fact that segments "A" and "B" are not interfered with, and since they can be used independent of "C" to reconstruct the digital audio, makes it possible for the system to survive this interference scenario.

Time Diversity

As broadcast engineers are well aware, the RF environment in which radio signals propagate can cause a variety of problems which conspire against clear reception of those signals. In AM radio, interference from atmospheric sources and power lines, and obstruction by frequently encountered objects such as concrete bridges and overpasses, result in annoying interruptions to the audio program, while in FM, multipath fading similarly degrades performance. Certainly, one of the goals in implementing a digital audio broadcasting (DAB) system is to minimize if not eliminate this type of behavior. In so doing, broadcasters will not only be improving their product but also be providing an added incentive, besides the more obvious promise of improved audio quality, for listeners to "upgrade" to a new digital service.

One of the most straightforward methods of improving a radio signal's susceptibility to a number of interference problems, in particular multipath, is by increasing its bandwidth. This is the approach which

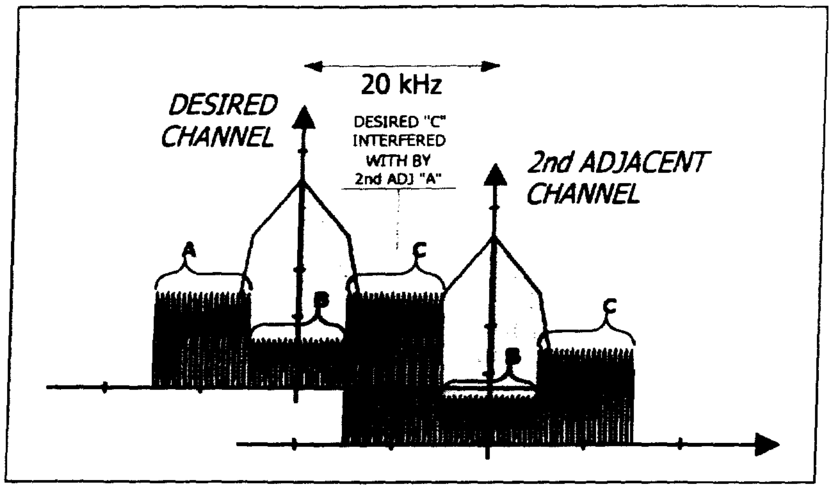

Figure 15. Illustration of 2nd Adjacent Channel Interference for USADR AM IBOC

has been taken in the implementation of the Eureka-147 DAB system - during the Eureka-147 development, it was established that an RF bandwidth of 1.5 MHz, in conjunction with sophisticated digital signal processing techniques, would effectively combat multipath and other interference problems.

This broadband approach to interference mitigation is unsuitable for use in an AM or FM IBOC DAB system, since such a broadband signal would be completely incompatible with the existing 20 kHz-wide AM and 200 kHz-wide FM analog signals. However, the next-generation IBOC systems all make use of a technique that is also effective, one that*is* compatible with in-band DAB. The cornerstone of this approach is a process known as *time diversity*, and it takes advantage of the fact that multipath fading and signal obstruction events are relatively short in duration, on the order of 1 to 5 seconds. Analyses and simulations done by USADR [10, 14] indicate that by applying time diversity in conjunction with interleaving and error-correcting codes, corruption of the audio signal by these types of interference can be virtually eliminated.

Time diversity involves sending two copies of the same signal at different times, and can be implemented in a number of ways. USADR intend to support time diversity by simulcasting the audio program on both the digital *and* analog audio portions of the IBOC signal; DRE has indicated that two digital versions of the signal will be sent, with analog (or FM subcarrier) simulcasting available as other, optional approaches.

The concept is illustrated in Figure 16, with reference to USADR's digital / analog simulcasting approach—the number sequences in the figure represent an audio program versus time. Two copies are transmitted - one on the analog carrier, one on the digital - but with the analog version being delayed with respect to the digital (the actual delay used in the USADR systems is on the order of 4-5 seconds).

The shading in the top figure represents a channel impairment, such as a bridge obstruction or a multipath fade. Notice how this event affects different portions of the audio program on the analog and digital signals, due to the time delay between them (affecting segments 6 & 7 in the digital, 3 & 4 in the analog). In the receiver, a delay equivalent to that introduced into the analog signal is introduced into the digital one, re-aligning the two signals. And finally, the receiver then replaces the impaired segments of the digital signal (blocks 6 & 7 in the figure) with the equivalent,*unimpaired* information from the analog signal, greatly reducing if not eliminating the impairment heard by the listener.

Another benefit of time diversity, when used with an analog simulcast channel, involves receiver behavior in cases of severe signal obstructions or extreme cases of interference. In these cases, systems without time diversity exhibit what is called a "cliff effect" failure, in that the audio signal is perfect one second, and completely gone ("muted") the next. In the

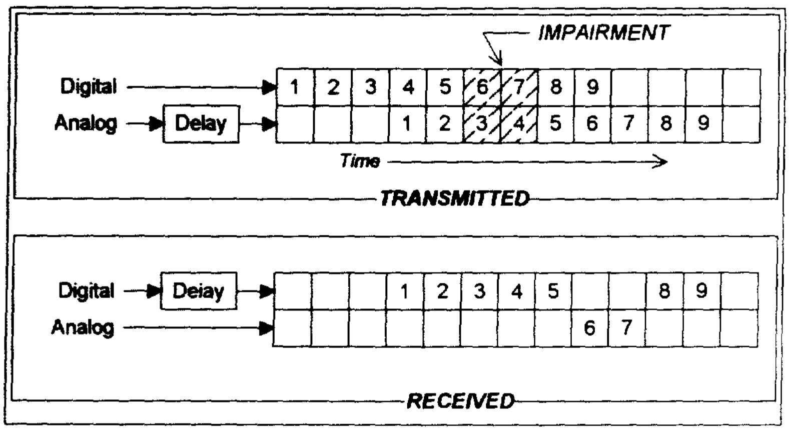

Figure 16. Illustration of Time Diversity

USADR systems, the existence of the "backup" analog signal for purposes of time diversity has the added effect of eliminating the cliff effect failure mode, since in those cases the receiver will blend to analog and the audio program, while degraded, will not go away all together, and is likely to remain with the listener throughout the impairment.

Frequency Diversity

It has already been mentioned how the digital sidebands (in the case of FM IBOC) and the three digital "segments" (for AM IBOC) are, to varying degrees, independent in the next-generation system designs. This may be described in more precise terms as a frequency diversity approach to signal design, since these independent regions are at different frequencies from one another.

In USADR's FM system, the two frequency diverse digital sidebands are related by what is known as "Complementary Punctured Codes" (CPCs) which are described in detail in [13]. This is a powerful coding technique which allows for the system to take advantage of frequency diversity when one of the sidebands is impaired, and also allows for enhanced system performance when both sidebands are present.

The USADR CPC approach involves taking the perceptually-coded digital audio data stream and applying to it a powerful rate 2/5 convolutional channel code. The output bits from the channel encoder are then grouped, or "punctured," in such a way as to form two independent data streams which are effectively channel encoded at a less protective, 4/5 rate, and are then modulated onto the upper and lower digital sidebands, respectively.

At the receiver, if both sidebands are received, the two rate 4/5 data streams are re-combined and then decoded using a rate 2/5 decoder; if only one of the sidebands is received, then it is decoded in a rate 4/5 decoder. Either way, the digital audio signal is recovered, however when both sidebands are present and used the error probability is reduced over that achievable with one sideband alone.

For the AM IBOC system, the three digital carrier segments (labeled A, B, and C in Figure 14) are used to achieve frequency diversity in a slightly different way. Under one possible scenario, the broadcaster decides for his or her particular station, based on the specific terrain and interference environment, what the likelihood of listeners successfully receiving one, two, or three segments is. For relatively benign environments, where listeners are likely to receive all three segments intact, the broadcaster may elect to transmit three different 16 kbps digital signals on each of the three segments—this is the "Near-CD quality" case shown in Table 4, where the subscripts "x" "y" and "z" denote unique bit streams. Note that each of these unique bit streams can be used to reconstruct the digital audio independently, however, the more segments available for reconstruction, the better the ultimate quality of the received signal.

On the other hand, if the reception environment is especially harsh, then the broadcaster may elect the "5 kHz Stereo" option from Table 4, and transmit the same 16 kbps data in each segment. In particular, this mode allows for the most robust coverage for distant listeners, since individual segments need not be received fully intact as long as a full set of carriers can be reconstructed from the three segments.

Table 4. Proposed Frequency diversity for USADR AM IBOC

MODE	MAX BIT RATE	A	B	C
Near-CD quality	48 kbps	$16K_x$	$16K_y$	$16K_z$
FM-like quality	32 kbps	$16K_x$	$16K_y$	$16K_x$
5 kHz Stereo	16 kbps	$16K_x$	$16K_x$	$16K_x$

Additional Features

There are many additional features of these next-generation IBOC systems which are expected to have a positive impact on their viability, in the following performance areas:

- Acquisition time: as already mentioned, these systems are sending multiple copies of the same signal with differing levels of error protection (when copies are both sent digitally), or simulcast in both analog and digital formats. One of the consequences of this is that the acquisition time of the system is enhanced. For example, in the simulcast case, it is likely that the analog signal will acquire very rapidly, much more so than the (heavily protected) digital signal, which is using interleaving of bits (among other techniques) to achieve error protection but which has as an undesirable consequence a delaying effect on acquisition. Such a receiver will use the analog signal for the first few seconds, and then switch to the digital signal once available.

Similarly, a system with two digital versions of the same signal will be designed such that one version is not as heavily protected as the other, and could be considered a "backup" version which is less robust, but acquires more quickly and will be available sooner (from an acquisition time standpoint) than the more robust version.

- Interference from 1st-adjacent channel: the frequency diversity of the next-generation FM IBOC systems, already discussed, helps to alleviate the 1st-adjacent interference problems observed in the EIA/NRSC tests, illustrated graphically in Figure 17. Another technique which is being pursued by USADR, to reduce the interference from the analog component of the 1st-adjacent signal on the desired digital component, is known as a "First Adjacent Canceller" (FAC).

  The FAC can be thought of as a tracking notch filter, which will track and remove the 1st-adjacent analog signal from the received desired signal, allowing for the recovery of the digital sideband being interfered with. Interestingly, the FAC actually is more effective when the interfering signal is stronger than when it is weaker, and consequently performance in the presence of a 1st-adjacent channel interferer may actually improve (to a point) as the interferer gets stronger.

- Data services: each of these systems will have an embedded digital data-carrying capacity, over and above that needed for digital audio. USADR expects their next-generation FM IBOC system to support the data services shown in Table 5. Their AM system is expected to have two data channels, as well—an auxiliary data channel at 2.4 kbps, and an opportunistic ancillary data channel whose capacity will vary but will on average be approximately 2 kbps.

  Less is known at present about the data broadcasting options for the DRE systems, but for their FM system they have indicated that an FM data subcarrier (residing in the baseband spectrum of the analog FM signal) has been incorporated and that this subcarrier will support a 64 kbps data rate, which could be used to provide a data service separate from the digital audio, or alternatively could be used as additional redundancy for the digital audio signal itself.

- FM/AM IBOC commonality: both USADR and DRE have expressed a commitment to insuring that their FM and AM IBOC systems can be easily and cost-effectively combined into a unified IBOC receiver design. For example, the USADR AM and FM systems are designed so that their digital clocks are related, which should allow for fewer parts and reduced interference in the final implementation.

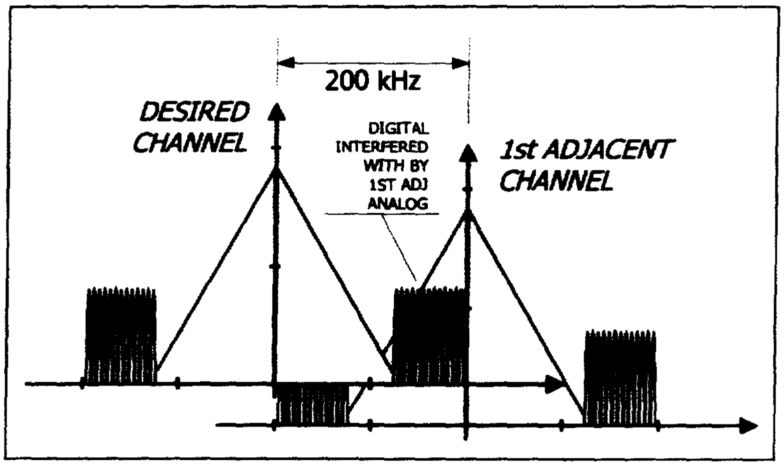

Figure 17. Illustration of 1st-Adjacent Channel Interference for USADR FM IBOC

DIGITAL AM

Another topic of interest to broadcasters pursuing an IBOC solution for DAB is that of international digital HF (shortwave) broadcasting, being referred in the industry by the general term of "Digital AM." A new, worldwide forum called "Digital Radio Mondiale" has been established to coordinate the development efforts of potential digital AM systems, and to determine the feasibility of establishing a single, worldwide, HF digital AM standard. The work of this group is of interest to commercial broadcasters operating in the medium wave AM band, because the technical problems to be overcome in transmitting digitally in the HF band (propagation effects in particular) are similar to, and in fact, more severe than, those encountered by a medium wave service.

Three separate efforts are currently underway to develop digital AM systems for HF broadcasting, by Thomcast (of France), Voice of America/Jet Propulsion Laboratory (VOA/JPL, United States), and Deutsche Telekom AG/Center for Broadcasting and Audiovisual (DTAG/ZRA, Germany). These

Table 5. Proposed USADR FM IBOC Data Broadcasting Options

TYPE	DATA RATE	DESCRIPTION	APPLICATIONS
Program Associated Data (PAD)	8 kbps	Data associated with radio station's main channel audio signal	• Receiver display • Station ID, song title & artist} • Receiver configuration (e.g., multiplex operation)
Ancillary Data	2-32 kbps	"Opportunistic" data channel contained within audio codec; actual rate is a function of audio program	• Traffic • Weather • Financial reports/updates • Other low-rate, non-real-time applications such as paging, email
Auxiliary Data	64 kbps	Independent data channel with guaranteed throughput; real-time, robust in mobile environment	• Traffic • Weather • Financial reports/updates • Other low-rate, non-real-time applications such as paging, email • "High-rate" datacasting, multimedia

systems have been described in a number of recent technical papers [1, 3]. Briefly, these systems are:

- Thomcast Skywave 2000 - this system offers a "progressive strategy" for the introduction of digital AM and has some similarities with the in-band/on-channel (IBOC) approach to digital audio broadcasting advocated by commercial U.S. broadcasters. In the analog-compatible implementation of the Thomcast system, a 10 kHz HF radio channel would contain both an analog sideband and a digital sideband (as shown in Figure 18). The analog sideband, either single-sideband or vestigal-sideband modulated, is receivable by a conventional HF receiver—tests done to-date indicate that this approach results in good analog audio quality in spite of the presence of the digital sideband, which acts as a noise interferer.

  The digital sideband consists of two "kernel" groups of carriers, utilizing either 64 QAM modulation with a total bit rate of approximately 12 kbps ("normal mode"), or 16 QAM modulation with a lower bit rate of 9 kbps ("fall-back mode", offering more robust performance). Using this approach, as broadcasters migrate to all-digital, additional kernels of digital modulation would replace the analog sideband, resulting in an all-digital system with increased capacity.

- Voice of America/Jet Propulsion Laboratory - the HF system being proposed by VOA/JPL is an adaptation of their DAB satellite system, one of the systems which was tested under the EIA/NRSC DAR test effort discussed above. Unlike the Thomcast system just described, this system is an all-digital scheme with no analog modulated (and presumably backward-compatible) component. Technical parameters of the VOA/JPL system include PSK modulation (BPSK and QPSK are both under consideration, with recent tests being conducted using BPSK at 8 kbps), forward-error correction using Viterbi and Reed-Solomon techniques (often referred to as concatenated

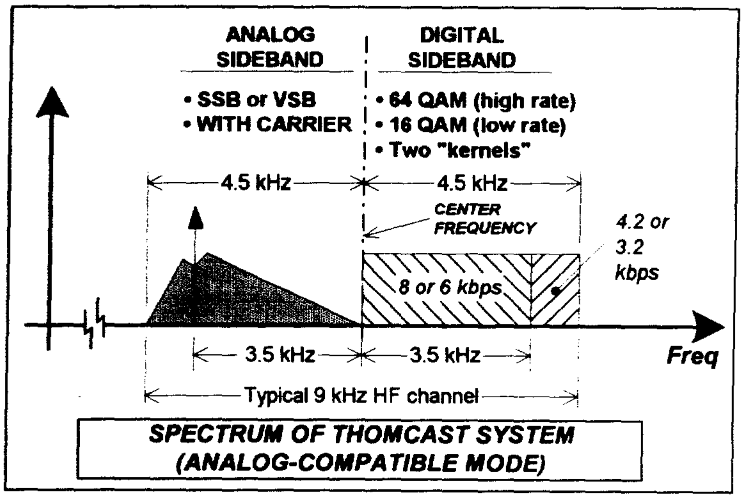

Figure 18. Example of Digital AM System Being Proposed for SW Band

[11] Keller, T. B., *Summary of FM Band IBOC Laboratory Tests Results*, 1996 NAB Broadcast Engineering Conference Proceedings, April 1996, pp. 5-13

[12] Kroeger, B., and Vigil, A.J.,*Improved IBOC DAB Technology for AM and FM Broadcasting*, 1996 SBE Convention, Los Angeles, CA, September 1996

[13] Kroeger, B., and Cammarata, D.,*Robust Modem and Coding Techniques for FM Hybrid IBOC DAB*, IEEE Transactions on Broadcasting, Vol. 43, No. 4, December 1997, pp. 412-420

[14] Kroger, B.W., and Peyla, P.J., *Compatibility of FM Hybrid In-band On-channel (IBOC) System for Digital Audio Broadcasting*, IEEE Transactions on Broadcasting, Vol. 43, No. 4, December 1997, pp. 421-430

[15] Kroeger, B., and Cammarata, D., *IBOC Interleaver Design and Simulation Results*, Radio World, Vol. 22 No. 2, January 21, 1998, pp. 20-21

[16] Layer, D. H. and Wilson, D.,*IBOC DAB: Its Potential for Broadcasters*, 1996 NAB Broadcast Engineering Conference Proceedings, April 1996, pp. 14-20

[17] Marcucci, C., *The Next IBOC Entrant: DRE Offers an Alternative to USADR*, Radio Business Report, February 16, 1998, pp. 6-10

[18] Murotake, David K. and Maxson, David P.,*On-carrier Digital FM technology: A New Approach for Digital Audio Broadcasting and Extra High-speed Data Transmission*, 1996 NAB Broadcast Engineering Conference Proceedings, April 1996, pp. 21-26

[19] *Radio broadcast systems; Digital Audio Broadcasting (DAB) to mobile, portable, and fixed receivers*, Final Draft pr ETS 300 401, European Telecommunications Standards Institute, Nov. 1994

[20] Salek, S., and Mansergh, D., *Field Testing of Proposed Digital Audio Radio Systems - Part I: Mobile Data Collection System*, 1997 NAB Broadcast Engineering Conference Proceedings, April 1997, pp. 49-57